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Optimization of high efficiency slab-on-ground floor by multi-objective analysis for zero energy buildings in mediterranean climate

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ABSTRACT

The international scientific community believes unequivocally that, at the origin of the climate change, there are anthropic factors mainly linked to the construction sector and to the disproportionate use of fossil energy sources.

The selection of building materials plays a key role in the reduction of energy consumption, especially in the Mediterranean area, where the internal overeating risk is high if the solar radiation is not controlled and the free supply of internal heat is poorly managed.

Traditionally, in the Italian context, the slab-on-ground floor is made in concrete or more rarely in stone. However, it is usually recommended to minimize the use of concrete as it has a strong environmental impact, reinforced concrete is still the most recommended solution for foundations, both for regulatory and practical reasons.

The present study proposes a methodology for the design of high efficiency slab-on-ground floor for warm climate through optimization code performed with the software modeFRONTIER.

Starting from the traditional floor structures, the multi-objective methodology stands as an advanced step for the identification of new configurations, favoring the management of many variables, such as thermal, environmental and economic aspects. The results are characterized by high presence of local and eco-friendly materials and reduced costs. At the end, this work demonstrates that it is possible to obtain high performance solutions with also very few numbers of layers.

1. Introduction

The strong increase in population and industrialization has led to arise in electricity demand [1]. In the European Union, the building sector accounts 40% of the total energy consumption and 36% of the EU's CO_2 emissions [2]. The European Union is determined to direct the development of a sustainable, competitive, secure and decarbonized energy system. In accordance with the guidelines of the of the World Health Organization of 2009, the EU affirms that high efficiency buildings offer high level of IAQ (Indoor Air Quality), ensuring greater comfort, health and well-being to the occupants. The Energy Performance of Buildings Directive underlines that the thermal bridges, the inadequate insulation and thus the air infiltration can generate surface temperatures below the air dew temperature, as well as humidity. For these reasons, it is crucial to guarantee a complete and homogeneous insulation of the building, considering balconies, windows, roofs, walls, doors and floors, avoiding that the temperature of any internal surface of the building falls below the dew temperature [3].

1.1. The sustainability protocols

Sustainability protocols are internationally recognized tools for assessing environmental, ecological and social quality in the construction sector. Most of them are based on rating systems, i.e. a set of points with a corresponding score. The aim of the internationally established sustainability rating systems is to encourage measures with a low impact on human health and on the environment, promoting a change in the housing market due to improving energy efficiency. In fact, these protocols disseminate the culture of sustainable building, ensuring the application of strategies to reduce the environmental impact in the construction of the building or a group of buildings (districts). The protocols are characterized by a great attention to energy efficiency, which has the greatest weight on the overall assessment of the building. Furthermore, the protocols evaluate the environmental impact considering the whole life cycle of the building, from construction to its disposal or redevelopment.

Currently, the LEED protocol (Leadership in Energy and

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Environmental Design), developed in the United States by the U.S. Green Building Council, is the most widely adopted in the world and can also be applied in Italy [4].

Another system, among the most widespread at international level as well as the precursor of all the certification of sustainability for buildings, is the BREEAM (Building Research Establishment Environmental Assessment Methodology), issued by the British BRE (Building Research Establishment), also introduced on the Italian market, based on the rating system [5].

CASBEE (Comprehensive assessment system for built environment efficiency) [6] is a method of assessing environmental sustainability applied to buildings, developed in Japan by the JSBC (Japan Sustainable Building Consortium). The system includes four assessment tools that analyze all aspects of the design considering each phase of a building life cycle.

The GREEN STAR is a national and voluntary assessment system developed by Green Building Council Australia, which helps to improve environmental efficiency in buildings and thus the community safety and well-being [7].

The ITACA Protocol is a tool for assessing the level of energy and environmental sustainability of buildings. The Protocol guarantees the objectivity of the evaluation using indicators and verification methods that comply with the technical standards and the national laws. Thanks to the ITACA Protocol, the Italian Regions have a valid tool to support territorial policies to promote environmental sustainability in the construction sector. It was created by ITACA (Institute for Innovation and Procurement Transparency and Environmental Compatibility - National Association of Regions and Autonomous Provinces), within the Interregional Working Group for Sustainable Building established in December 2001, with the technical support of iiSBE Italia (International Initiative for a Sustainable Built Environment Italy) and ITC-CNR, and approved on January 15, 2004 by the Conference of Regions and Autonomous Provinces.

The Protocol has been adopted by numerous regions and municipal administrations in various initiatives aimed at promoting and encouraging sustainable construction through regional laws, building regulations, and urban planning tenders. The Protocol is derived from the SBTool international evaluation model, developed as part of the Green Building Challenge research process, and contextualized to the Italian territory in relation to the reference legislation and its environmental characteristics.

The ITACA Protocol promotes the use of eco-friendly materials. It favors the use of recycled and/or recovery materials to reduce the consumption of new resources. A recycled material is a material that, through a manufacturing process, is transformed into a final product or a component. Recovered material means a material that would have been considered a waste, but which, on the contrary, was collected and recovered as material to be reused directly in a new construction or in a restructuring operation. To pursue the goal of reducing the consumption of non-renewable raw materials, the protocol considers materials from renewable sources. The supply of building material from local producers allows shortening the distance that a given component must cover to reach the construction site, to reduce emissions during the transport of such material. "Locally sourced materials" means materials produced within 300 km away from the construction site. Another criteria is called "sustainable materials", which measures the percentage of eco-sustainable material, in other words the building materials with eco-friendly certifications [8].

Principi et al. [9] carried out a study on the application of the ITACA Protocol for several residential buildings. All buildings are compared to the relative reference building, characterized by the same geometric shape. The possibility to reduce the energy consumption and GHG emissions is monitored using the protocol.

Staring from the previous considerations, the present study focuses on the evaluation of sustainability of each building material investigated, according to the environmental sustainability score suggested by the ITACA Protocol. Another important issue is to keep down the implementation costs, since the economic feasibility plays a key role in the design phase for the choice of the slab-on-ground floor.

1.2. Importance of building material selection

The design of Zero Energy Buildings needs a thorough analysis before choosing the construction materials [10], especially in the early stage of the design process, when strategic decisions are made. For the selection of the best slab-on-ground configurations and materials, it is important to remember that, generally, in particular in warm climate, the ground temperature is higher than the external temperature in winter and lower in summer. This suggests attention to select layers and materials to take under control the heating and cooling demands. The choice of high insulation thicknesses not necessarily lead to a reduction of yearly energy consumption in warm climate. Many studies [11,12] carry out parametric studies on envelope, fenestration and technical systems of buildings in warm climate, where the heating and cooling demands are, generally, very similar. The roofs and the external walls show heat exchanges always higher with respect of ground floor, in winter and summer, because of a higher difference of temperature between the internal and external side of the element. In summer, in particular, roofs and external walls are stressed by intense solar radiation. The only possibility to dispose of heat is the heat exchange with the ground. It suggests doing not use high thickness of insulation materials.

It is known that all phases of the building lifecycle have a significant impact on the environment and on the human life, both directly (through the material and the power consumption) and indirectly (using inefficient infrastructure). The impacts of different materials depend on various factors such as the origin of the material and the processing cycle, but also the adequacy of the material once it has been installed. The life cycle of materials is evaluated from the origin to the end of its useful life, assessing all the effects on human health and on the protection of the environment.

The sustainable materials are characterized by high recycled/reused content [13,14], by fast renewable times [15], low emission of VOC (Volatile Organic Compound) [13,15], low consumption [13,15,16], low maintenance costs [17] and safe in its useful life [13,14,17].

1.3. Importance of slab-on-ground floor component

The slab-on-ground floor is a critical part of the opaque envelope most affected by the moisture damages, heat losses and thermal comfort problems. Often only, a thin layer of gravel divides the foundation from the ground, which is rich in water content. Under hygroscopic conditions, the thermal conductivity of wet subsoil is very higher than the one of the coarse-grained drainage materials [18].

For this reason, it is suggested to use of insulating materials, that prevent the capillary water rising and simultaneously the heat dissipation to the ground. The findings are always valid but, in warm climate, the difference of thermal conductivity between coarse-grained drainage materials (lower) and moist or wet subsoil layer (higher) is less pronounced.

Choi et al. [19] presents a detailed analysis of the heat transfer across the slab-on-grade floors characterized by irregular ground surface levels, considering the horizontal and vertical insulation length, and the distance between the slab and the stepped ground.

Alkaff et al. [20] state that the ground can be considered as heat tank, which it is useful in the control of the internal microclimate of the building.

Hait [21] shows how the heat naturally stored in the ground may be collected, stored and retrieved, to control the summer heat gain and the winter heat losses, without the use of mechanical systems.

The proposed work is designed for slab-on-ground floor, in order to optimize the thermal behavior of the whole building and to permit a

good thermal balance with the subsoil stratum. It emphasizes the role of the slab-on-ground floor in the reduction of the overheating inside the building in warm climates.

In summary, the aim is the identification of a set of configurations of slab-on-ground floor with high thermal performances in order to break down and/or reduce the energy consumption and emissions caused by the air conditioning systems.

1.4. The multi-objective methodology

In the last years, multi-objective optimization techniques are considered an effective tool to identify the best configurations for engineering applications in the energy efficiency field. The multi-objective optimization is a process that aims to find the optimal solution of a problem consisting of multiple objectives.

Wright et al. [22] have demonstrated that the building design may be considered as a multi-criteria problem.

The multi-objective analysis can be performed to reach the nZEB targets, investigating also the cost for the implementation of measures for several climatic areas [23].

The envelope works as a mediator between indoor and outdoor environment, for this reason a correct design of a highly efficient building starts from the choice of construction materials and thicknesses of the envelope.

The internal areal heat capacity is the parameter that best characterize the external walls behavior for warm climate [24,25].

Multi-objective optimization algorithm is used to identify the optimal design of the building envelope coupled to both energy consumption and life cycle impact on the environment [26].

Castro-Lacouture et al. [27] affirm that the choice of the construction materials, characterized by low environmental impact, can be described by an optimization model.

In addition, the multi-objective analysis can help the designer to couple the building component characteristics with the energy and financial aspects [28].

2. Thermal performance of slab-on-ground floor – dynamic thermal characteristics

The climatic zones of the Italian territory are defined according to the degree-day classification. This study has been carried out for a climatic zone C, heating degree-days equal to 1153, characterized by non-extreme winters and high aridity in summer. The design temperature for the internal environment during the winter period is equal to 20 °C, while 26 °C for the summer season. The studied climatic area can be also classified as Csa in accordance with Köppen-Geiger classification [29], i.e. hot Mediterranean/ dry-summer subtropical climate.

This study defines the high efficiency slab-on-ground floor behavior for warm climates. A correct selection of building materials plays a key role in the reduction of energy consumption, especially in this area, where the internal overeating risk is high if the solar radiation is not controlled and the free supply of internal heat is poorly managed.

Passive cooling techniques can reduce the peak cooling load in buildings. The energy flow in the passive design may take place by radiation, conduction or convection without the use of any electrical device. Environmental heat sinks are outdoor air (heat transfer by convection through openings), water (heat transfer by evaporation), night sky (heat transfer through long wave radiation through the roof and/or another surface adjacent to a building) and the ground (heat transfer by conduction through the building envelope) [30].

The insulation and the thermal mass are key parameters for the improvement of the thermal comfort in buildings. The insulation reduces the heat transfer rate between inside and outside, the thermal mass allows the heat storage with a delay of the heat transfer. Both help to keep the building cool in summer and warm in winter.

The building performance in semi-arid warm climate has been conducted in [31], which carried out an investigation combining the thermal insulation effect to a high thermal inertia of the building.

It has been noted that it is convenient to place the thermal mass in correspondence of passive gains. The mass must be externally insulated to reduce the heat transfer from the inside towards the outside.

Reinforced concrete, for regulatory and practical reasons, is the most recommended solution for making foundations. Nowadays, it is recommended to minimize the use of concrete as it maintains moisture for a long time, it has poor breathability, high conductivity and it is easily attacked by atmospheric agents. For these reasons, it requires complex thermal and acoustic insulation and the use of specific chemical additives with a strong environmental impact. Furthermore, the mechanical performances of concrete are highly affected by the climatic conditions. The cold climate delays the hydration reaction of the cement but, after the initial setting process, the slow hydration of the cement facilitates hardening and improves the mechanical strength. The warm climate accelerates the setting and reaction of cement hydration, leading to a non-homogeneous hardening of the mass, thus negatively affecting the mechanical strength.

The evaluation of the dynamic thermal performance of slab-on-ground floor has been carried out through the calculation procedure defined by EN ISO 13786:2018 [32]. The temperature values and the heat flow rate are considered as a sinusoidal function of the time. A period equal to 86,400 s (corresponding to one day) has been evaluated, imposing a conductive thermal exchange condition.

Table 1 presents the thermo-physical characteristics of the building materials, in terms of thermal conductivity (W/m K), specific heat (J/kg K), density (kg/m^3) and thickness (mm), used for the multi criteria analysis. In addition, the table reports the most common thicknesses available on the market from specific datasheets or regional price list.

2.1. Traditional slab-on-ground floor

The slab-on-ground floor must be safe, not yielding, not slippery, and must avoid moisture and heat dispersions. There are various constructive solutions depend on the building use, the system requirements, the available budget and the time required for the realization of the work.

In southern Italy, the main typologies of floors can be divided into two macro-groups: floors placed directly on a thick layer of gravel (S1) and floor completely separated from the ground by an air cavity (S2).

The S1 can be not ventilated, weakly ventilated and ventilated. The S2 is, usually, ventilated.

The realization of the ventilated cavity allows to improve the quality of housing by creating a ventilation area under the walking surface. The recirculation of air mitigates the dumping humidity by conveying it with possible harmful gases, such as Radon gas, outside the buildings.

In general, the natural ventilation occurs through openings for air passage. If the only presence of openings is not able to guarantee adequate ventilation of the crawl space, for example for the friction with the gravel, the active systems can be adopted (aspirators). The adoption of active systems can also allow the choice of the type of ventilation. It is possible to create a depressurization, by aspirating air from inside the crawl space, or blowing air inside it to create a pressurization. In both cases, it is essential to guarantee an adequate sealing of the floors of the rooms placed above the crawl space, to guarantee an effective pressure difference.

Fig. 1 shows the main categories S1 and S2 in the ancient (A) and current (C) constructions.

The same classification is reported in Table 2 that shows the thermal characteristics of the selected typologies of slab-on-ground floor, calculated with EN ISO 13786:2018.

The Italian Regulation imposes, for new nZEBs built in climatic zone C, values of static thermal transmittance U lower than 0.38 W/m^2 K and a periodic thermal transmittance Y_{12} less than 0.18 W/m^2 K or

Table 1
Thermophysical properties of building materials.

Construction materials	Commercial thicknesses mm	λ W/m K	C J/kg K	ρ kg/m^3
Air (stationary state)	50; 60; 70; 80; 90; 100; 120; 130; 140; 150;300	0.026	1000	1.3
Bio-brick	100; 140; 290	0.187	1112	1171
Calcium silicate panels	80; 100; 120; 160; 180; 200; 240; 260; 300	0.045	1000	107.5
Cellular glass	40; 60; 80; 100; 120; 140	0.55	850	120
Cement mortar	30	1.4	836	2000
Coconut fiber	20; 30; 40	0.043	1450	85
Concrete	30; 40; 50; 60; 70; 80; 90; 100	1.67	880	2200
Concrete closed structure. expanded clay	50	0.325	920	1000
Cork panels expanded	10; 20; 30; 40; 50; 60; 80; 100; 120; 140; 160	0.039	1900	120
EPS 1 (Expanded polystyrene)	20; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200	0.032	1350	28
EPS 2	20; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200	0.033	1350	24
EPS 3	30; 40; 50; 60; 80; 100; 120; 140; 160	0.034	1350	20
EPS + graphite (Synthesized polystyrene foam with graphite)	20; 30; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200	0.003	1350	28
Expanded clay	50	0.09	1000	300
Exfoliated vermiculite	2	0.057	787	85
Fiberglass	40; 50; 60; 85; 100	0.032	1030	32
Flax fiber	40; 60; 80; 100	0.038	1410	30
Granulated cellular glass	15; 20; 25; 30; 40; 50	0.078	850	160
Granules of expanded perlite	5; 7; 10; 15; 20	0.045	837	92.5
Gravel	50; 75; 100; 150	1.2	1000	1700
Hemp fibers	30; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200; 220; 240	0.03	2200	38
Hydraulic lime plaster	15	0.054	836	1150
Hollow bricks 120/150*250*380	120; 150	0.08	850	1280
Hollow bricks 160/200/250/300*250*380	160;200;250;300	0.08	1500	1280
Kenaf fiber	20; 30; 40; 50; 60	0.039	2050	80
Lime and gypsum plaster	15	0.007	837	1400
Lightweight concrete	400	0.444	920	1300
Plaster mixed ready	30	0.14	836	1000
Pure gypsum plaster	12.5	0.035	837	1200
Rigid polyurethane foam panels 1	20; 30; 40; 50; 60; 70; 80; 90; 100; 120	0.023	1500	40
Rigid polyurethane foam panels 2	30; 40; 50; 60	0.028	1500	40
Rigid polyurethane foam panels 3	80; 100	0.026	1500	40
Rigid polyurethane foam panels 4	30; 40; 50; 60; 70	0.028	1500	40
Rigid polyurethane foam panels 5	20; 30; 40; 50; 60; 80; 100; 120; 140; 160	0.023	1500	40
Rigid polyurethane foam panels 6	20; 30; 40; 50; 60; 70	0.028	1500	40
Rigid polyurethane foam panels 7	80; 90; 100	0.026	1500	40
Rigid polyurethane foam panels 8	120; 140; 160	0.025	1500	40
Rigid polyurethane foam panels 9	20; 30; 40; 50; 60; 70; 80; 90; 100; 120; 140; 160	0.023	1500	40
Rock wool 1	50; 60; 80; 100	0.035	1030	70
Rock wool 2	60; 80; 100	0.035	1030	100
Rock wool 3	30; 40; 50; 60; 80; 100	0.037	1030	140
Rock wool 4	20	0.036	1030	100
Sheep wool	100; 150	0.037	1720	17.9
Soft cellulose fibers panels	30; 40; 50; 60; 80; 100; 120; 140; 160	0.039	2000	70
Tuff	110; 150; 180; 200; 250	0.336	1300	1215
Wood fiber panels flexible	40; 50; 60; 80; 100; 120; 140; 160; 180; 200; 220; 240	0.038	2100	50
Wood fiber hardboard	40; 60; 80; 100; 120; 140; 160; 180; 200	0.039	2100	160
Wood wool	25; 35; 50	0.08	1800	385
XPS 1	20; 25; 30; 40; 50; 60; 80; 100; 140; 160; 180; 200	0.032	1100	30
XPS 2	80; 90; 100; 220; 240; 260; 280; 300	0.035	1100	30
XPS 3	120; 220; 240; 260; 280; 300	0.036	1100	30
XPS 4	200; 220	0.035	1100	30
XPS 5	80; 100; 120; 240; 260; 280; 300	0.036	1100	30
XPS 6	50; 60; 140; 150; 160; 180	0.034	1100	30
XPS 7	200; 220	0.035	1100	30
XPS 8	80; 100; 120; 240; 260; 280; 300	0.036	1100	30

superficial mass M_s greater than 230 kg/m^2. The verified values in accordance with the Regulation are highlighted in bold.

Fig. 2 puts in evidence the external temperature trend and the comparison between all superficial internal temperatures of the slab-on-ground floors above presented.

Looking at Fig. 2, it has been noted that the floor configurations with thermal insulant show lower oscillations, because of the lower heat exchange with the ground. Such a condition, always valid in winter, is not necessarily useful in summer because, with high internal gains, limits the possibility to dispose of them toward the ground.

Consequently, like shown in Table 3, also the configurations with thin thicknesses of thermal insulation have been investigated. Table reports the thermal performances of the S1 C with 3 cm of insulting layer. The aim is the comparison of the superficial internal temperature between different insulation thicknesses for the same structure S1 C, as reported in Fig. 3.

The choice to compare also floor configurations with the regulation limits not verified, in particular U, come from the observation that highly insulated floors do not show a good summer performance in buildings predominantly for summer use.

3. Methodology approach

This study puts in evidence the various types of slab-on-ground floors used in the Mediterranean climate, showing the evolution from typical ancient constructions to new floors for nZEBs.

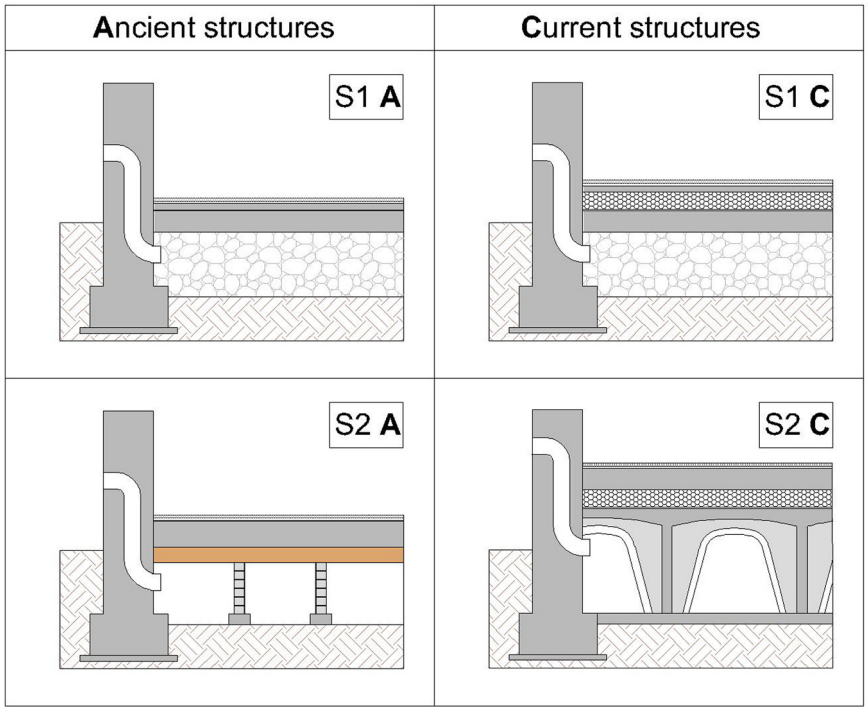

Fig. 1. Examples of traditional slab-on-ground floor.

The aim of this paper is to reach high efficiency slab-on-ground floors by multi-objective analyses. Fig. 4 summarizes the different steps of the study.

3.1. The multi-objective optimization

The workflow of the multi objective analysis developed in modeFRONTIER rel.4.3 [33] is shown in Fig. 5. It describes the logical system of a problem, using nodes, with different functions, and special connectors (links). The inputs are the parameters that define the model to be studied and optimized. The model of slab-on-ground floor is chosen with five layers, without finishing elements.

The calculator is a MATLAB script [34], which allows to perform mathematical calculations proposed by the UNI 13786, considering the variables of the problem.

The scheduler is a node always present in the workflow, it defines the type of experimentation to be performed and the type of optimizer to be applied.

The statistical technique used to perform the simulations is the DOE (Design of Experiment), which allows to satisfy the relations between the input factors (objectives and constraints) and the output with minimal effort and, therefore, with the minimum of the possible number of experiments.

The first step of the simulation is the DOE (Design of Experiments)

Table 2
Thermal performances of traditional slab-on-ground floor.

	Ancient structures				**Current structures**			
	S1 A			**S2 A**	**S1C**			**S2C**
Layer 8	–			–	–			Tiles 0.015 m
Layer 7	–			–	Tiles 0.015 m			Adesive 0.01 m
Layer 6	Tiles 0.015 m			Tiles 0.015 m	Adesive 0.01 m			Concrete 0.1 m
Layer 5	Adesive 0.01 m			Adesive 0.01 m	Concrete 0.03 m			XPS1 0.08 m
Layer 4	Concrete 0.03 m			Protection membrane 0.005 m	XPS1 0.08 m			Protection membrane 0.005 m
Layer 3	Protection membrane 0.005 m			Concrete 0.12 m	Protection membrane 0.005 m			Concrete 0.06 m
Layer 2	Concrete 0.1 m			Brick slab 0.07 m	Concrete 0.1 m			Iglu' ventilated under-floor cavities 0.45 m
Layer 1	Gravel 0.3 m			Air 0.3 m	Gravel 0.3 m			Concrete 0.05 m
	Not ventilated	**Weakly ventilated**	**Ventilated**	**Ventilated**	**Not ventilated**	**Weakly ventilated**	**Ventilated**	**Ventilated**
U (W/m^2 K)	1.836	1.654	1.541	0.782	**0.328**	**0.327**	**0.318**	**0.332**
$\mathbf{Y_{12}}$ (W/m^2 K)	0.300	0.24	0.200	**0.150**	**0.020**	**0.02**	**0.02**	**0.05**
$\mathbf{Y_{22}}$ (W/m^2 K)	12.141	12.161	12.2845	1.969	12.099	12.0781	12.2629	9.171
$\mathbf{Y_{11}}$ (W/m^2 K)	4.279	4.28	4.2802	4.305	4.272	4.2723	4.2722	4.807
fd	0.166	0.1427	0.1301	0.195	0.072	0.0688	0.0487	0.145
$\mathbf{M_s}$ (kg/m^2)	**848**	**848**	**848**	**405**	**850**	**850**	**850**	**516**
Δt (h)	11h43'	12h21'	12h39'	9h54'	14h45'	14h53'	14h42'	10h33"
k1 (kJ/m^2 K)	62.970	61.9401	61.394	61.217	58.820	58.809	58.744	66.768
k2 (kJ/m^2 K)	170.140	169.1534	170.303	29.166	166.400	166.098	168.568	126.629
d (m)	0.460	0.460	0.460	0.52	0.540	0.540	0.540	0.77

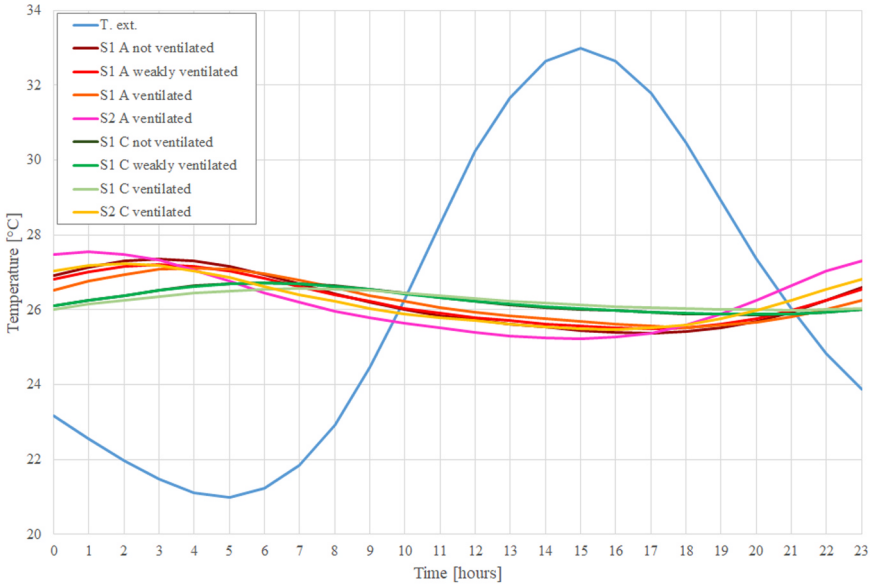

Fig. 2. Temperature trends of ancient and current slab-on-ground floor.

Table 3
Thermal performances of slab-on-ground floor S1C with 3 cm of insulting layer.

	S1C (iso 3 cm)		
Layer 7	Tiles 0.015 m		
Layer 6	Adesive 0.01 m		
Layer 5	Concrete 0.03 m		
Layer 4	XPS1 0.03 m		
Layer 3	Protection membrane 0.005 m		
Layer 2	Concrete 0.1 m		
Layer 1	Gravel 0.3 m		
	Not ventilated	**Weakly ventilated**	**Ventilated**
U (W/m^2 K)	0.675	0.670	0.630
Y_{12} (W/m^2 K)	**0.06**	**0.05**	**0.04**
Y_{22} (W/m^2 K)	12,100	12.0839	12.2648
Y_{11} (W/m^2 K)	4128	4.1282	4.1278
fd	0.085	0.0819	0.0598
M_s (kg/m^2)	**848**	**848**	**848**
Δt (h)	14h10'	14 h 18′	15 h 07′
k1 (kJ/m^2 K)	57.08	57.048	56.848
k2 (kJ/m^2 K)	166.63	166.294	168.588
d (m)	0.490	0.490	0.490

sequence, which allows to satisfy the relations between the input factors (objectives and constraints) and the output with minimal effort and, therefore, with the minimum of the possible number of experiments.

In this study, the DOE consists of 10.000 individuals. These combinations have been elaborated by the MOGA II (Genetic Algorithm Multi Objectives), setting up a number of 10 generations, for an amount of 100000 iterations. MOGA II starts from a series of possible solutions (DOE), representing the "initial population" and provides the evolution during the execution. At each iteration, it is selecting the present population of individuals, used to generate new elements of the same population, which replace an equal number of individuals already present, representing a new population for the next iteration. This succession of generations evolves towards an optimal local or global solution assigned to the problem. The outcome of each simulation is a set of possible solutions, which represent the Pareto front. These combinations represent the best compromise between the various designated targets and all the constraints imposed on the simulation model.

Finally, the "Logic End" node belongs to the set of logical nodes and it is used to confirm the success of the run and the acceptance of the solutions found. The outputs describe the behavior of the model, produced by the solvers. The output of the system has been developed according to the needs of the designer, setting constraints and objectives. The optimization has been performed in terms of static transmittance, periodic thermal transmittance, decrement factor, time shift, areal heat capacity, thermal admittance, surface mass, thickness, percentage of Itaca score and costs.

3.1.1. The input values

The simulation requires the definition of the input variables. The input vector is composed of five components, which correspond, respectively, to the imposed five layers of slab-on-ground floor chosen as model for the analysis. Each layer assumes a random value between 1 and 310. Each input value corresponds to a specific material, with defined properties, such as thermal conductivity, density, specific heat, thickness, cost and environmental sustainability. To create a rich database, a survey of various building materials available on the market has been conducted. The input values are listed according to their intrinsic features listed in Table 1 for the physical characteristics of the building materials and Table 4 for the costs available on the market or on regional pricelists. They do not consider the dismantling and possible recycling costs.

3.1.2. The output values

In Table 5 are shown the constraints and objectives, in terms of cost, sustainability score and the thermal properties, chosen for a building located in a warm climate. The limits of stationary transmittance (U) of 0.38 W/m^2 K and the dynamic transmittance (Y_{12}) of 0.18 W/m^2 K are in accordance with the Italian regulation for nZEBs, considering a climate zone C. The maximum total thickness of the floor (d) has been set at 70 cm for economical and volumetric considerations. The maximum achievable phase shift is fixed at 20 h because the best values are around 12 h and too high values, over 22 h, can generate overlapping effects of subsequent thermal waves.

The remaining properties are maximized or minimized without setting numerical constraints. The optimal solutions are considered the best compromise between objectives and constraints of the problem.

The section eco-friendly materials (B.4) of the Itaca Protocol is composed by the following subsections:

1. Criteria B.4.1: reuse of existing structures (score 10%);
2. Criteria B.4.6: recycled materials (score 40%);
3. Criteria B.4.7: materials from renewable sources (score 10%);

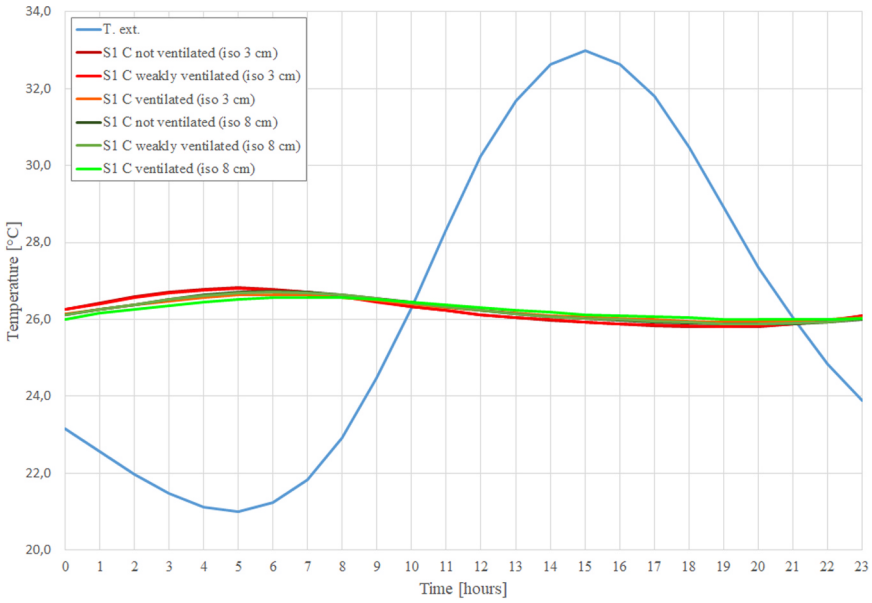
T. ext.
S1 C not ventilated (iso 3 cm)
S1 C weakly ventilated (iso 3 cm)
S1 C ventilated (iso 3 cm)
S1 C not ventilated (iso 8 cm)
S1 C weakly ventilated (iso 8 cm)
S1 C ventilated (iso 8 cm)
Temperature [°C]
Time [hours]

Fig. 3. Comparison between the internal surface temperatures of S1C floor with different insulation and ventilation.

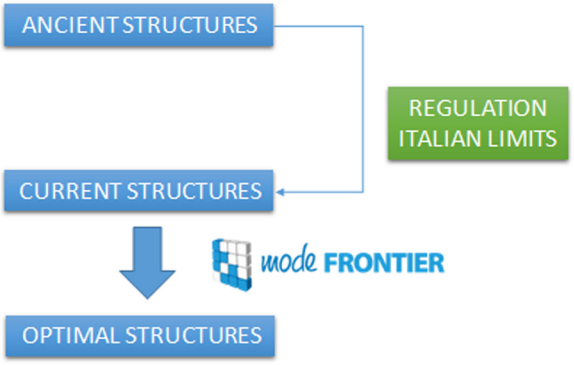

Fig. 4. Methodology flowchart.

4. Criteria B.4.8: local materials (score 10%);
5. Criteria B.4.10: recyclable materials (score 10%);
6. Criteria B.4.11: certified materials (score 10%);
7. Criteria RP.2: sustainable materials (score 10%);

Each single criteria ranges from 0 to 5, which is weighted into the section eco-friendly materials (B.4) with a precise score, equal to 40% for the Criteria B.4.6% and 10% for everyone else.

This study evaluates the criteria B.4.6, B.4.7 and B.4.8 for their not strong dependence from the commercial brand. In addition, the B.4.10 is not considered because calculated using the effective surface recyclable, this implies the definition of e precise geometry of the building. The maximum sum of all seven criteria of B.4. is equal to 5, the maximum possible sum reachable with the three criteria B.4.6, B.4.7 and B.4.8 is equal to 3.

The criteria B.4.6 and B.4.7 are calculated considering the volume (m^3) of building materials recycled or from renewable materials. The criteria B.4.8 considers the weight (kg) of each material, evaluating the distance between the site of production of each material and the city of Lecce (southern Italy). The maximum score is reached for distances less than 150 km, the minimum (zero point) for distances over 300 km.

Another setting point is the minimization of the final cost. The goal is to suggest high efficiency and cost-effective solutions, in order to obtain real and economically solutions, feasible and expendable on the market.

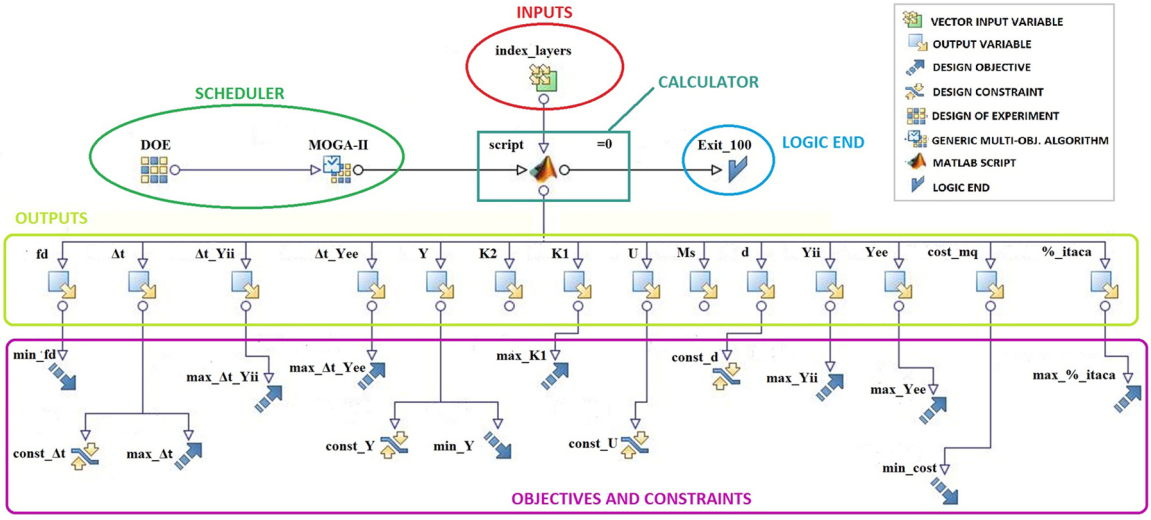

Fig. 5. Flow-chart of the multi objective analysis.

Table 4
Evaluation of the costs of the building material.

Construction materials	Commercial thicknesses (mm)	Cost (€/m^2)	Cost (€/m^3)
Bio-brick	100; 140; 290	24.4; 32.94; 64.66	–
Calcium silicate panels	80; 100; 120; 160; 180; 200; 240; 260; 300	58.23; 62.14; 65.68; 73.55; 77.36; 81.16; 101.45; 111.59; 131.63	–
Cellular glass	40; 60; 80; 100; 120; 140	33.13 48.71 69.01 182.81 103.52	–
Cement mortar	30		75.38
Coconut fiber	20; 30; 40	18.20; 21.00; 26.50	–
Concrete	30; 40; 50; 60; 70; 80; 90; 100	–	120
Concrete closed structure. expanded clay	50	–	189
Cork panels expanded	10; 20; 30; 40; 50; 60; 80; 100; 120; 140; 160	10.3; 13.3; 17.7; 23.60; 29.5; 35.4; 47.2; 59; 70.8; 82.6; 94.4	–
EPS 1	20; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200	–	155
EPS 2	20; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200	–	175
EPS 3	30; 40; 50; 60; 80; 100; 120; 140; 160	–	120
EPS + graphite	20; 30; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200	–	170
Expanded clay	50	–	148
Exfoliated vermiculite	2	–	165.29
Fiberglass	40; 50; 60; 85; 100	4.95; 6.24; 7.51; 10.59; 12.48	–
Flax fiber	40; 60; 80; 100	–	162.5
Granulated cellular glass	15; 20; 25; 30; 40; 50	–	202
Granules of expanded perlite	5; 7; 10; 15; 20	–	171
Gravel	50; 75; 100; 150	–	26,1
Hemp fibers	30; 40; 50; 60; 80; 100; 120; 140; 160; 180; 200; 220; 240	4.5; 5.75; 7.15; 8.55; 9.9; 11.75; 13.25; 15.35; 17.65; 19.8; 22; 24.2; 26.25	–
Hydraulic lime plaster	15	–	112,4
Hollow bricks 120/150/160 * 250 * 380	120; 150; 160	5.27	–
Hollow bricks 200 * 250*380	200	5.45	
Hollow bricks 250 * 250 * 380	250	6.64	–
Hollow bricks 300 * 250 * 380	300	11.52	–
Kenaf fiber	20; 30; 40; 50; 60	5.10; 7.65; 10.20; 12.70; 15.30	–
Lime and gypsum plaster	15	19.72	–
Lightweight concrete	400	–	182
Plaster mixed ready	30	–	182
Pure gypsum plaster	12.5	18.48	
Rigid polyurethane foam panels 1	20; 30; 40; 50; 60; 70; 80; 90; 100; 120	7.2; 9.2; 11.3; 13.2; 15.15 ;17.9; 19.7; 22; 24.1; 29.35	–
Rigid polyurethane foam panels 2	30; 40; 50; 60	9.1; 11.3; 13.4; 15.55	–
Rigid polyurethane foam panels 3	80; 100	20.15; 24.6	–
Rigid polyurethane foam panels 4	30; 40; 50; 60; 70	10.1; 12.3; 14.3; 16.3; 19.4	–
Rigid polyurethane foam panels 5	20; 30; 40; 50; 60; 80; 100; 120; 140; 160	9.5; 11.7; 14.1; 16.55; 18.6; 22.40; 26.9; 31.35; 36.2; 41.70	–
Rigid polyurethane foam panels 6	20; 30; 40; 50; 60; 70	7.3; 9.15; 11.3; 13.25; 15.4; 18.3	–
Rigid polyurethane foam panels 7	80; 90; 100	28.95; 31; 33.40	–
Rigid polyurethane foam panels 8	120; 140; 160	38.15; 42.7; 47.65	–
Rigid polyurethane foam panels 9	20; 30; 40; 50; 60; 70; 80; 90; 100; 120; 140; 160	7.4; 9.4; 11.5; 13.7; 15.5; 18.5; 20.2; 22.5; 2.8; 29.5; 34.5; 40	–
Rock wool 1	50; 60; 80; 100	9.2; 10.59; 14.14; 17.65	–
Rock wool 2	60; 80; 100	40.87; 48.43; 56.95	–
Rock wool 3	30; 40; 50; 60; 80; 100	7.23; 9.63; 12.05; 14.46; 19.27; 24.10	–
Rock wool 4	20	4.01	–
Sheep wool	100; 150	4.95; 6.24; 7.51; 10.59; 12.48	–
Soft cellulose fibers panels	30; 40; 50; 60; 80; 100; 120; 140; 160	7.5; 9.7; 12.15; 14.55; 18.45; 21.05; 25.2; 29.45; 33.7	–
Tuff	110; 150; 180; 200; 250	15.94; 16.9; 31.5; 18.58; 19.63	–
Wood fiber panels flexible	40; 50; 60; 80; 100; 120; 140; 160; 180; 200; 220; 240	4.17; 5.24; 6.26; 8.35; 10.43; 12.52; 14.69; 16.69; 18.95; 20.87; 23.12; 25.04	–
Wood fiber hardboard	40; 60; 80; 100; 120; 140; 160; 180; 200	5.20; 7.79; 10.39; 12.99; 15.59; 18.18; 20.78; 23.38; 25.98	–
Wood wool	25; 35; 50	18.6; 23.1; 31.9	–
XPS 1	20; 25; 30; 40; 50; 60; 80; 100; 140; 160; 180; 200	–	90
XPS 2	80; 90; 100; 220; 240; 260; 280; 300	–	90
XPS 3	120; 220; 240; 260; 280; 300	–	90
XPS 4	200; 220	–	150
XPS 5	80; 100; 120; 240; 260; 280; 300	–	150
XPS 6	50; 60; 140; 150; 160; 180	–	150
XPS 7	200; 220	–	150
XPS 8	80; 100; 120; 240; 260; 280; 300	–	150

4. Results and discussions

4.1. General configurations

The first analysis has been carried out on the configuration of floor with five layers without restrictions on the position of each material, using the constraints and objectives of Table 5.

The results are analyzed by a correlation matrix, which is a very advantageous statistical method used to measure the linear relationship between two elements. It is a square matrix, symmetric (M X M), the r_{ji} element is the correlation coefficient between the i-th and j-th variable. The correlation coefficients range from -1 to $+1$, on the main diagonal they are equal to 1. The coefficients show the correlation degree between two elements. When the value is 1, there is a perfect positive correlation between the two elements, when it is -1, a perfect negative correlation. For values of correlation coefficient between 0 and 1, the two variables have a direct correlation, when the correlation coefficient has a value ranging between -1 and 0 the two variables have an inverse relationship. The value 0 implies that there is no relationship between the two variables.

Table 5
Objective functions and constraints of multi-objective optimization analysis for warm climates.

Output	Objectives	Constraints
Fd	↘	–
Δt	↗	< 20 h
Y_{12}	↘	< 0.18 W/m^2 K
κ1	↗	–
U	–	< 0.38 W/m^2 K
D	–	< 0.70 m
Y_{11}	↗	–
Y_{22}	↗	–
% ITACA	↗	–
Cost	↘	–

Fig. 6 shows the correlation matrix between seventeen elements of the problem:

1. Five elements relating to the input data of the five layers of the stratigraphy;
2. Ten elements concerning the thermal characteristics;
3. One element for the evaluation of sustainability based on the Protocol ITACA;
4. One element for the evaluation of the cost.

The correlation values have been highlighted with different colors, which correspond to the correlation degree. The red color underlines the maximum positive correlation degree, while the blue one the maximum negative correlation. The histogram uses the same color of the correlation matrix to highlight the percentage of the correlation recurrence. It points out that, almost 40% of the times, the correlation value is very near the 0 with values slightly higher than 0 (between 0 and 0.2) and almost 40% slightly less than 0 (between −0.2 and 0), showing a very low correlation.

A correlation coefficient equal to 1 is present between Y_{11}- k_1 and Y_{22}- k_2, meaning a very positive correlation between the two elements. A very high positive correlation, equal to 0.901, results between fd and Y_{12}. High correlations, ranging from 0.6 to 0.8 are present between Layer 1 - k_1, Layer 1 - Y_{11}, Layer 5 - k_2 and Layer 5 - Y_{22}.

A correlation equal to −1 is never present, but correlations ranging from −0.4 to −0.6 are between U-d, Ms-Y_{12} and Ms-fd.

4.2. Slab-on-ground floor with gravel

This section provides the analysis of the S1 configuration optimized by the multi objective methodology.

The model of slab-on-ground floor, simulated for the multi-objective analysis, consists of five layers with gravel on the first layer contacting directly with the ground, and the second and fifth layer bound with concrete, in accordance with the ancient (S1 A) and current (S1 C) ones. Each layer can assume several thicknesses, the constraint on material is on the first, second and fifth layer.

Table 6 points out the optimal solutions selected from among the 22744 Pareto solutions. In bold, the five layers from the multi-objective analysis are highlighted. For the final configuration three layers have been added just to complete the real configuration (layers a, b and c) with the positioning of the water protection membrane and the finishing layers (generally chosen in the customization step).

To avoid the presence of superficial or interstitial condensation and critical surface humidity, the hygrothermal performance test (Glaser) is carried out for all configurations, in accordance with the norm EN ISO 13788 [35]. The check is done considering the temperature data of the city of Lecce (southern Italy), as shown in Fig. 6.

The cost for the ventilated gravel configurations is increased of 1.00 euro/m^2, considering the cost of the fan installation. All configurations reach a very high value of Itaca score.

The analysis of the operative temperature inside a prototype building presented in [36] demonstrates that in warm climates, it is not strictly necessary to aim very low transmittance values. For this reason, the U value is preferable to be not far from the regulation limit (Fig. 7).

All configurations showed very good values of time shift, greater than 12 h and high values of k1. It is interesting to note, that S1 MF-01 presents the same material in the layers 3 and 4, thus the number of layers can be decreased, leading to a reduction of costs due to the double positioning of materials.

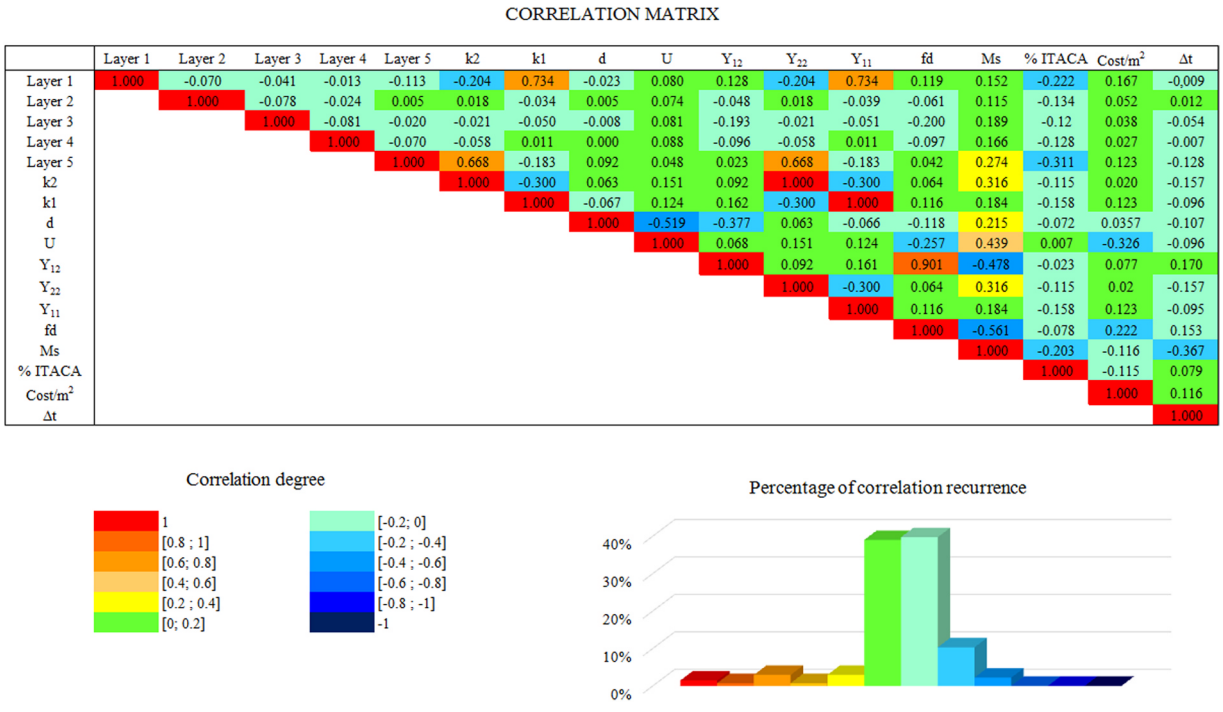

Fig. 6. Correlation matrix among Pareto analysis variables of a generic simulation.

Table 6
Optimized slab-on-ground with gravel (S1).

	S1 MF-01			S1 MF-02			S1 MF-03		
Layer c	Tiles 0.015 m			Tiles 0.015 m			Tiles 0.015 m		
Layer b	Adesive 0.01 m			Adesive 0.01 m			Adesive 0.01 m		
Layer 5	**Concrete 0.07 m** (< 100 km local material)			**Concrete 0.06 m** (< 100 km local material)			**Concrete 0.05 m** (< 100 km local material)		
Layer 4	**Kenaf fiber 0.04 m** (Renawable material)			**Soft cellulose fibers panels 0.05 m** (100% recycled and renewable material)			**Wood fiber hardoboard 0.08 m** (15% recycled and renewable material)		
Layer 3	**Kenaf fiber 0.05 m** (Renawable material)			**Wood fiber hardboard 0.06 m** (15% recycled and renewable material)			**Granules of exp. perlite 0.05 m** (Renawable material)		
Layer a	Protection membrane 0.005 m			Protection membrane 0.005 m			Protection membrane 0.005 m		
Layer 2	**Concrete closed structure exp. clay 0.05 m** (< 100 km local material)			**Concrete 0.07 m** (< 100 km local material)			**Concrete 0.06 m** (< 100 km local material)		
Layer 1	**Gravel 0.15 m** (100% recycled and < 100 km local material)			**Gravel 0.15 m** (100% recycled and < 100 km local material)			**Gravel 0.15 m** (100% recycled and < 100 km local material)		
	Not ventilated	**Weakly ventilated**	**Ventilated**	**Not ventilated**	**Weakly ventilated**	**Ventilated**	**Not ventilated**	**Weakly ventilated**	**Ventilated**
U (W/m^2 K)	**0.351**	**0.350**	**0.339**	**0.309**	**0.308**	**0.299**	**0.280**	**0.273**	**0.272**
Y_{12} (W/m^2 K)	**0.07**	**0.07**	**0.05**	**0.04**	**0.04**	**0.02**	**0.04**	**0.04**	**0.02**
Y_{22} (W/m^2 K)	13.469	12.9957	10.5138	13.012	12.4664	10.0565	13.212	12.6581	10.1474
Y_{11} (W/m^2 K)	4.775	4.7754	4.7751	4.728	4.7280	4.7280	4.641	4.613	4.6413
fd	0.207	0.198	0.1332	0.141	0.1324	0.0835	0.148	0.1398	0.0883
M_s (Kg/m^2)	**518**	**518**	**518**	**606**	**606**	**606**	**566**	**566**	**566**
Δt (h)	12h11'	12h22'	13h28'	14h13'	14h23'	15h15'	14h30'	14h41'	15h36'
k1 (kJ/m^2 K)	66.584	66.516	66.114	65.314	65.3	65.118	64.081	64.042	69.881
k2 (kJ/m^2 K)	185.824	179.246	144.722	179.06	171.521	138.218	181.769	171.106	139.44
d (m)	0.39	0.390	0.390	0.420	0.420	0.420	0.420	0.420	0.420
Itaca score (%)	2.418	2.418	2.418	2.782	2.782	2.782	2.473	2.473	2.473
Cost (€/m^2)	44.67	44.67	45.67	39.46	39.46	40.46	36.06	36.06	37.06

Fig. 8 highlights the trend of the internal surface temperature for the S1 MF-01, S1 MF-02 and S1 MF-03 configurations.

Table 7 shows further simplest evolutions of the S1 configurations, suggested by the authors after the analysis of the above presented structures. In particular, the structures S1 EVO – 01 and S1 EVO – 02 are composed with very few numbers of layers and without the presence of concrete on the second layer. The idea is to propose simpler configurations with respect to the optimized ones, with similar thermal properties, reducing the installation costs, but preserving the thermal behavior.

All configurations reach a very high value of Itaca score and very low costs. The hygrothermal performance test (Glaser) is verified for all configurations, as shown in Fig. 9. Fig. 10 shows the comparison between the internal surface temperatures of the designed structures S1.

4.3. Slab-on-ground floor with Iglu'

The Iglu' is used to avoid the rising damp and to physically split the floor from the ground. It ensures the healthiness of the interior spaces, thanks to the creation of a ventilation space under the walking surface.

The recirculation of air mitigates the internal humidity by conveying it with possible harmful gases such as Radon gas, outside the buildings.

The recommended area of the openings, to guarantee a good natural ventilation, is at least 1500 mm^2 per meter of perimeter wall. To allow

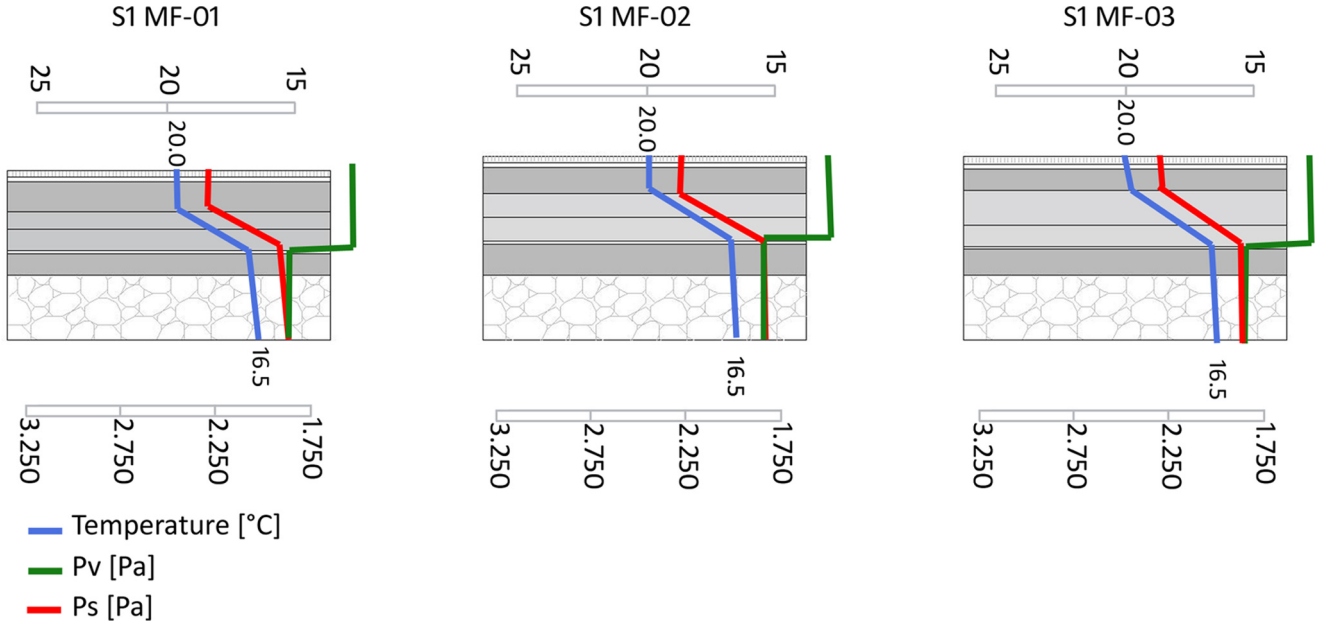

Fig. 7. Optimized slab-on-ground floors with gravel S1 – Glaser check at February, Lecce – Italy.

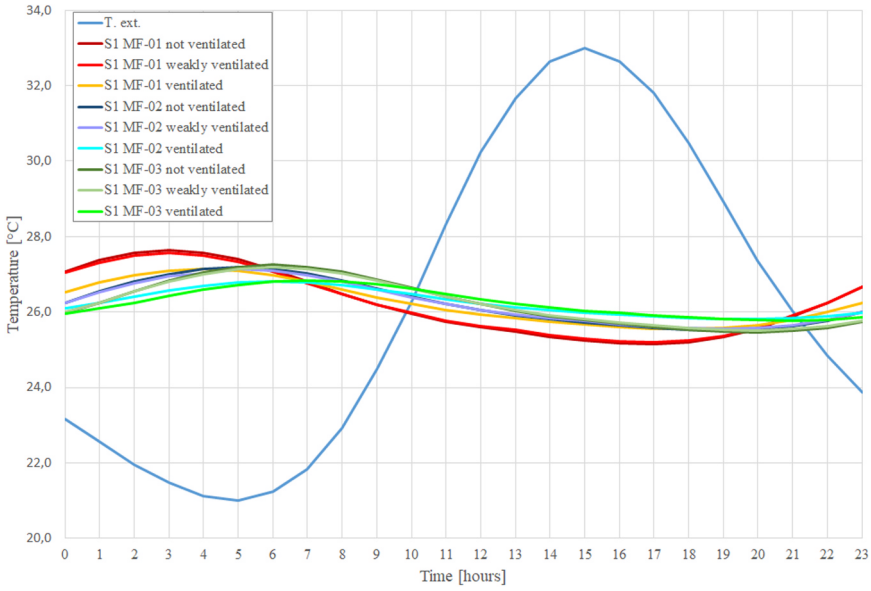

Fig. 8. Comparison between the internal surface temperatures of the optimized S1.

the greatest flow of air, the ventilation openings must be conveniently located on opposite sides and in a north-south direction, with the opening to the south in a higher position than the one to the north.

The model of slab-on-ground floor, adopted for the multi-objective analysis, consists of five layers with the cavity of air on the second layer while the first, the second and the fifth layer constrained to the presence of concrete, in accordance with the used structures S2 C.

In Table 8 a set of solutions between 13489 Pareto solutions is selected. In bold, the five layers from the multi objective analysis are highlighted. Like for the previous configurations, three layers (a, b and c) have been added to complete the real configuration. The selected solutions are characterized by very low thicknesses of concrete, which cannot be eliminated for structural reasons. The hygrothermal performance test (Glaser) is verified for all configurations, as shown in Fig. 11 Fig. 12 shows the trend of the internal surface temperature of S2 MF-04, S2 MF-05 and S2 MF-06.

The authors have also evaluated the configurations without the presence of concrete on the first layer in contact with the ground, but this proposal is not acceptable, because all configurations presented very low values of time shift, less than 10 h. In a warm climate, this

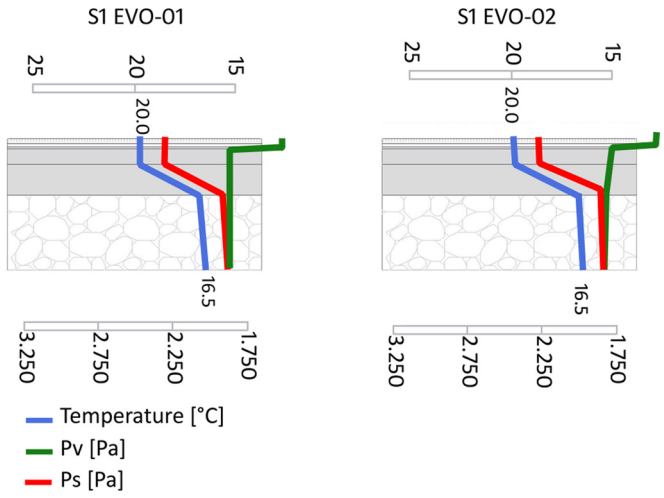

Fig. 9. Evolution of slab-on-ground floors with gravel S1 – Glaser check at February, Lecce - Italy.

Table 7
Evolution of slab-on-ground with gravel (S1).

	S1 EVO −01			**S1 EVO −02**		
Layer c	Tiles 0.015 m			Tiles 0.015 m		
Layer b	Adesive 0.01 m			Adesive 0.01 m		
Layer a	Protection membrane 0.005 m			Protection membrane 0.005 m		
Layer 3	**Concrete 0.05 m** (< 100 km local material)			**Concrete 0.05 m** (< 100 km local material)		
Layer 2	**Granules of expanded perlite 0.1 m** (Renawable material)			**XPS 1 0.1 m**		
Layer 1	**Gravel 0.24 m** (100% recycled and < 100 km local material)			**Gravel 0.24 m** (100% recycled and < 100 km local material)		
	Not ventilated	**Weakly ventilated**	**Ventilated**	**Not ventilated**	**Weakly ventilated**	**Ventilated**
U (W/m^2 K)	**0.375**	**0.373**	**0.361**	**0.280**	**0.279**	**0.272**
Y_{12} (W/m^2)	**0.06**	**0.06**	**0.04**	**0.05**	**0.05**	**0.03**
Y_{22} (W/m^2 K)	12.8927	12.7550	12.3089	12.9143	12.7741	12.3135
Y_{11} (W/m^2 K)	4.4046	4.4046	4.4043	4.4232	4.4232	4.4231
fd	0.1710	0.1650	0.1207	0.1690	0.1630	0.1182
M_s (kg/m^2)	**579**	**579**	**579**	**573**	**573**	**573**
Δt (h)	12h04'	12h14'	13h18'	11h47'	11h57'	13h02'
k1 (kJ/m^2)	61.359	61.310	60.989	61.427	61.392	61.1567
k2 (kJ/m^2 K)	177.910	170.958	169.468	178.079	176.107	169.506
d (m)	0.420	0.420	0.420	0.420	0.420	0.420
Itaca score (%)	2.756	2.756	2.756	2.5	2.5	2.5
Cost (€/m^2)	29.36	29.36	30.36	21.26	21.26	22.26

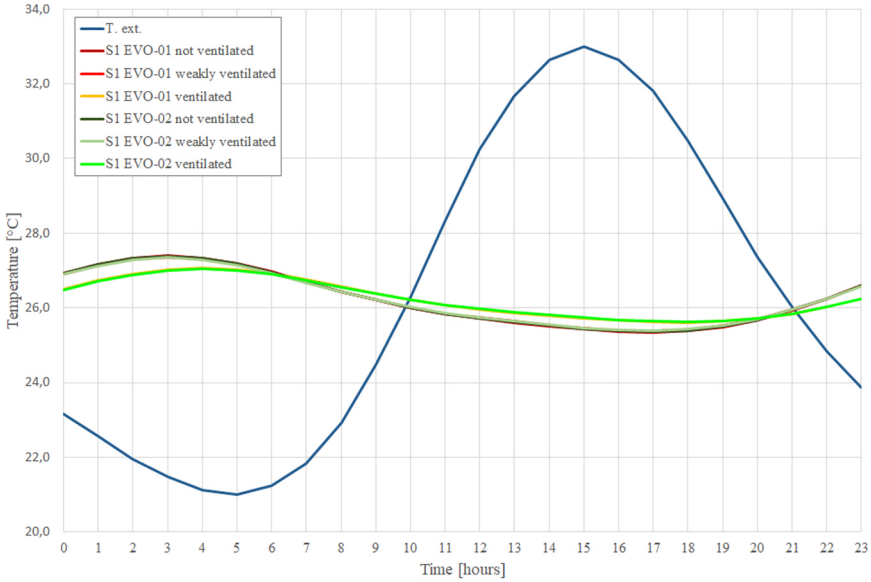

Fig. 10. Comparison between the internal surface temperatures of the suggested structures S1.

parameter is essential to avoid the overheating in the building, especially in the summer season.

5. Conclusions

This work aims to provide to the designers a set of slab-on-ground floor through the combination of commercial and eco-friendly building materials available on the market.

The set of optimal combinations has been the result of a multi-objective analysis, carried out using modeFRONTIER tool, which aims to find the right compromise between high-energy efficient slab-on-ground floor in compliance with ITACA protocols and low costs.

The technique of a multi-objective study allows the designer to achieve a wide range of optimal solutions. In addition, the methodology can be used for several objectives, different design requirements and other boundary conditions.

In this paper, the case study is focused on a warm climate. Different typologies of slab-on-ground floor have been presented in accordance with the traditional contractions.

This study focuses on the importance of the U values for slab-on-ground floor; in particular, it has been demonstrated that is crucial to select solutions with U values very close to the limit of the Italian regulation (i.e. 0.38 W/m^{2}K), and not lower, in order to permit an adequate exchange with the ground, in summer. It is fundamental for building located in warm climate, where the overheating must be avoided. In addition, it has been pointed out that it possible to reach very high performances both with low and very high total surface mass values.

Finally, this paper puts in evidence the several advantages from the use of the configuration with gravel. In fact, the solutions reach optimal thermal characteristics with high values of the Itaca score and low costs. A further evolution can be with very few numbers of layers and without the excessive presence of concrete, reducing, for example the concrete on the second layer for the configuration with gravel. The aim has been to suggest simpler configurations with respect to the optimized ones, with similar thermal properties, reducing the installation costs.

All chosen combinations are completed with the positioning of the

Table 8
Example of very high performance of slab-on-ground with iglù (S2).

	S2 MF-04	**S2 MF-05**	**S2 MF-05**
Layer c	Tiles 0.015 m	Tiles 0.015 m	Tiles 0.015 m
Layer b	Adesive 0.01 m	Adesive 0.01 m	Adesive 0.01 m
Layer 5	**Concrete 0.07 m** (< 100 km local material)	**Concrete 0.07 m** (< 100 km local material)	**Concrete 0.07 m** (< 100 km local material)
Layer 4	**Rigid polyurethane foam panels 8 0.14 m**	**Wood fiber hardboard 0.1 m** (15% recycled and renewable material)	**Cork panel exp. 0.1 m** (Renawable material)
Layer a	Protection membrane 0.005 m	Protection membrane 0.005 m	Protection membrane 0.005 m
Layer 3	**Concrete 0.06 m** (< 100 km local material)	**Concrete 0.05 m** (< 100 km local material)	**Concrete 0.05 m** (< 100 km local material)
Layer 2	**Iglu' ventilated under-floor cavities 0.26 m**	**Iglu' ventilated under-floor cavities 0.09 m**	**Iglu' ventilated under-floor cavities 0.2 m**
Layer 1	**Concrete 0.06 m** (< 100 km local material)	**Concrete 0.06 m**	**Concrete 0.06 m** (< 100 km local material)
U (W/m^2 K)	**0.166**	**0.328**	**0.337**
Y_{12} (W/m^2 K)	**0.03**	**0.08**	**0.08**
Y_{22} (W/m^2 K)	11.629	10.975	12.136
Y_{11} (W/m^2 K)	4.804	4.761	4.772
fd	0.211	0.249	0.2441
M_s (kg/m^2)	**475**	**404**	**460**
Δt (h)	11h21'	11h36'	11h09'
k1 (kJ/m^2 K)	66.535	66.568	66.749
k2 (kJ/m^2 K)	160.225	151.404	167.617
d (m)	0.62	0.40	0.51
Itaca score (%)	0.5	0.986	0.708
Cost (€/m^2)	65.5	34.59	80.6

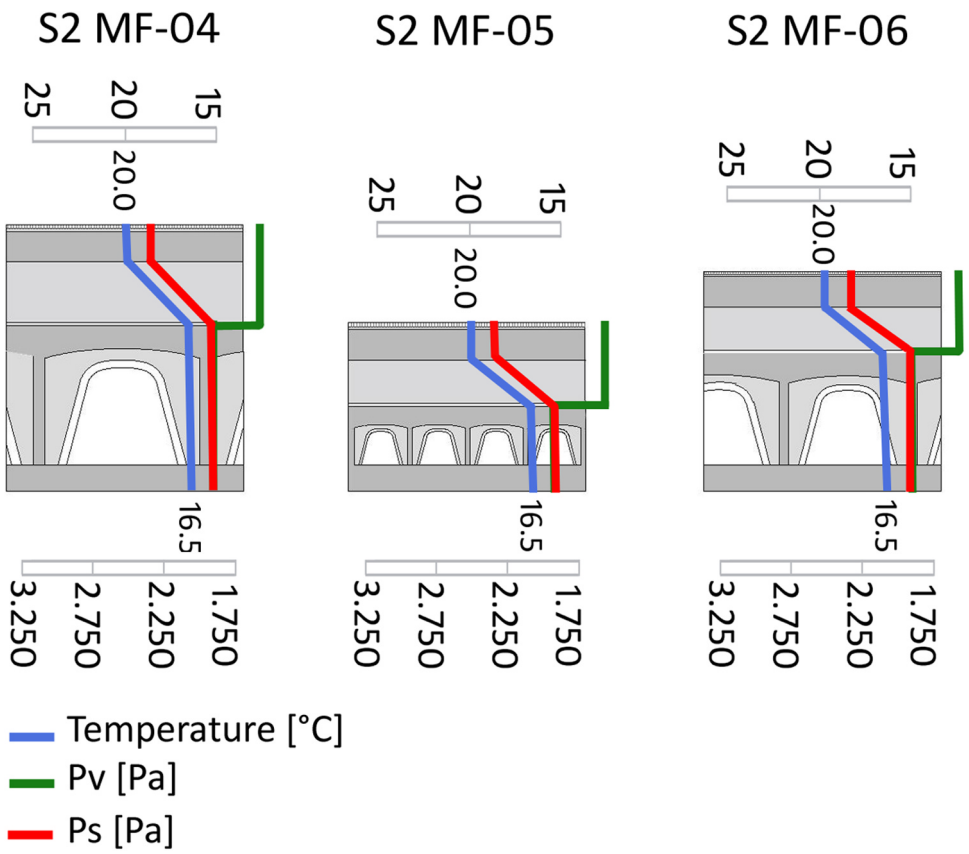

Fig. 11. Optimized slab-on-ground floors with Iglu' S2 - Glaser check at February, Lecce - Italy.

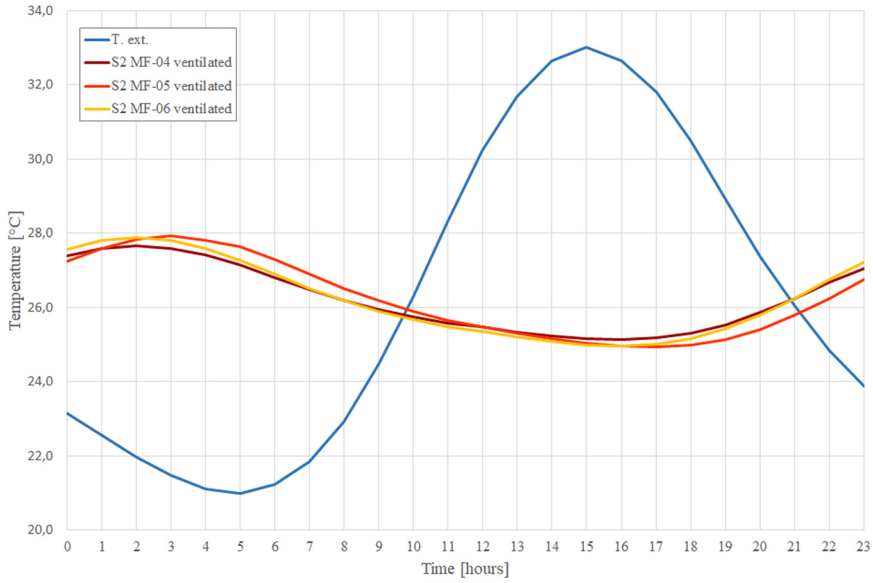

Fig. 12. Comparison between the internal surface temperatures of the optimized S2.

water protection membrane and the finishing layers. The hygrothermal performance test (Glaser) is verified for all combinations.

A correct positioning of the protection membrane is fundamental, since it works as barrier also for possible harmful gases, such as Radon gas. Where very high levels of radon are reached is necessary the realization of the ventilated cavity, which allows to improve the quality of housing by creating a ventilation area under the walking surface.

Further studies are needed to investigate the applicability of the model for other climatic zones and introducing the ground properties as variable of the problem.

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